

# Multiple stellar populations in three rich Large Magellanic Cloud star clusters<sup>1</sup>

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## ABSTRACT

We present deep color-magnitude diagrams for three rich intermediate-age star clusters in the LMC, constructed from archival ACS F435W and F814W imaging. All three clusters exhibit clear evidence for peculiar main-sequence turn-offs. NGC 1846 and 1806 each possess two distinct turn-off branches, while the turn-off for NGC 1783 shows a much larger spread in color than can be explained by the photometric uncertainties. We demonstrate that although all three clusters contain significant populations of unresolved binary stars, these cannot be the underlying cause of the observed turn-off morphologies. The simplest explanation is that each cluster is composed of at least two different stellar populations with very similar metal abundances but ages separated by up to  $\sim 300$  Myr. The origin of these unusual properties remains unidentified; however, the fact that at least three massive clusters containing multiple stellar populations are now known in the LMC suggests a potentially significant formation channel.

*Subject headings:* galaxies: star clusters — globular clusters: general — Magellanic Clouds

## 1. Introduction

It is a long-held notion that rich star clusters, including globular clusters, are composed of single stellar populations – that is, that each such object is made up of stars of a uniform age and chemical composition. New observations are challenging this accepted picture, however. It has recently been discovered that several of the most massive Galactic globular

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clusters harbor multiple stellar populations with a wide variety of unexpected characteristics. The most striking example is  $\omega$  Centauri, which exhibits at least four different populations covering a wide spread in metal abundance and age across the sub-giant branch (SGB) (Villanova et al. 2007), as well as a main sequence bifurcation which implies the presence of a vastly helium-enriched population (Piotto et al. 2005). NGC 2808 possesses a triple main sequence split, suggesting two helium-enriched populations (Piotto et al. 2007); while NGC 1851 and NGC 6388 show clear splits in their SGBs, possibly indicative of populations with ages  $\sim 1$  Gyr apart, or of sizeable intracluster variations in chemical composition (Milone et al. 2008; Piotto 2008; Salaris et al. 2008). In addition, several massive globular clusters in M31, including G1, apparently possess significant internal spreads in metal abundance (Meylan et al. 2001; Fuentes-Carrera et al. 2008). Overall, these observed properties pose serious challenges for conventional models of globular cluster formation and evolution.

Rich intermediate-age star clusters in the Magellanic Clouds have the potential to open a new angle on this problem. These objects have masses comparable to many Galactic globulars (although are an order of magnitude less massive than clusters like NGC 2808), but possess color-magnitude diagrams (CMDs) far more sensitive to internal dispersions in age, for example. We recently discovered that the massive LMC cluster NGC 1846 possesses a CMD exhibiting two clearly distinct main-sequence turn-offs (MSTOs) (Mackey & Broby Nielsen 2007), which we interpreted as belonging to two stellar populations with similar metal abundance but ages  $\approx 300$  Myr apart. Motivated by this discovery we have searched the HST/ACS archive for additional observations of both NGC 1846 and other rich intermediate-age LMC clusters. In this Letter we report on the first results from this search, presenting a new deep CMD for NGC 1846 as well as CMDs for two additional objects – NGC 1783 and 1806 – that exhibit peculiar MSTOs. Similar results for these clusters have simultaneously and independently been obtained by another group (Goudfrooij et al. 2008).

## 2. Observations and data reduction

ACS/WFC imaging of the three clusters was taken through the F435W and F814W filters as part of HST program GO 10595 (P.I. Goudfrooij), between 2005 September 29 – 2006 January 14. Each cluster was imaged three times per filter – two long exposures of duration 340s each, and one short exposure of duration 90s in F435W and 8s in F814W.

We used the ACS module of the DOLPHOT photometry software (Dolphin 2000) to photometer the images. DOLPHOT performs point-spread function (PSF) fitting using PSFs especially tailored to the ACS cameras, and works directly on flat-fielded images from the STScI archive relative to some deep reference image (we used the drizzled combination of

the two long-exposure F814W images for each cluster). DOLPHOT accounts for the hot-pixel and cosmic-ray masking information provided with each flat-fielded image, fits the sky locally around each detected source, and provides magnitudes corrected for charge-transfer efficiency (CTE) effects on the calibrated VEGAMAG scale of Sirianni et al. (2005).

For a given cluster we found that the narrowest CMD sequences were obtained by treating the four long-exposure images together and the two short-exposure images together in two separate DOLPHOT runs. We used the photometric quality information provided by DOLPHOT to clean the two resulting detection lists before combining them. In each list we selected objects of stellar type, with valid measurements on all input images, global sharpness parameter between  $\pm 0.3$  in each filter, and “crowding” parameter less than 0.5 mag in each filter. We combined the cleaned lists by selecting all long-exposure detections fainter than, and all short-exposure detections brighter than 0.5 mag below the long-exposure saturation level at  $m_{\text{F435W}} \approx 19$ . A small region of overlap between the lists was used to calculate and eliminate any small global offsets (typically  $\lesssim 0.02$  mag).

### 3. Analysis

Our CMDs for NGC 1846, 1783, and 1806 are presented in Fig. 1. In these plots, we have isolated the cluster sequences from the surrounding low-level field populations by imposing radial cuts of  $30''$  and  $60''$  as marked. Full CMDs are shown in the left-hand column, while the second column shows close-ups of the cluster MSTOs and the third column presents Hess diagrams of these MSTO regions. In the right-hand column are CMDs constructed by taking stars as far as possible from each cluster center over areas equivalent to those used for the central MSTO extractions. These outer CMDs likely still contain a few cluster members, and are hence not completely pure field samples. Nonetheless, they clearly demonstrate that the unusual CMD features described below are not the result of field star contamination.

All three clusters exhibit striking, unusual MSTOs. That for NGC 1846 possesses two clear branches, as demonstrated previously by Mackey & Broby Nielsen (2007) from shallower ACS observations ( $S/N \sim 150$  at the MSTO, compared with  $S/N \sim 250$  here). The MSTO for NGC 1806 also possesses two clear branches, spaced similarly to those of NGC 1846. In contrast, the MSTO for NGC 1783 is not evidently split into branches; instead, the spread in color of the MSTO for this cluster is much larger than can be explained by the photometric uncertainties (marked in Fig. 1; note also the narrowness of the main sequence below the turn-off). This may represent individual MSTO branches which are closely spaced and unresolved by the observations, or a smoothly spread distribution of stars. We find no evidence in the three clusters that stars belonging to different MSTO sections

(e.g., upper/lower branches) possess different spatial distributions. Mucciarelli et al. (2007) previously noted a spread in color about the MSTO of NGC 1783; however, their CMD was from shallower data such that the observed spread was consistent with that expected from the photometric uncertainties.

Apart from the peculiar MSTO morphologies, the CMDs in Fig. 1 are as expected for intermediate-age clusters. The main sequences, sub-giant branches (SGBs) and red giant branches (RGBs) are narrow and the red clumps are well defined, implying that the MSTO structures are not due to significant line-of-sight depth or differential reddening in these clusters. The narrow CMD sequences further suggest minimal internal dispersions in  $[\text{Fe}/\text{H}]$ ; however we note they place no constraints on the possibility of internal variations in other chemical abundances – for example, CN, O, Na, or  $[\alpha/\text{Fe}]$  – as are observed for several of the peculiar massive Galactic globular clusters (e.g., Piotto 2008).

Also evident on each cluster CMD is a clear spread of stars above and to the red of the main sequence, implying a non-negligible population of unresolved binary systems (e.g., Hurley & Tout 1998). To quantify this in a given cluster, we selected all stars within  $30''$  of the center and in the range  $22 \leq m_{\text{F435W}} \leq 23.2$  (i.e., along the upper main sequence). We fit a ridgeline to the main sequence, and constructed a histogram of the spread in stellar color about this peak. The dispersion to the blue represents photometric uncertainties only; to the red, there is an additional component due to binaries. Reflecting the blue-side dispersion to the red and subtracting this from the histogram thus allows the number of binary stars to be approximately determined. Because of the presence of photometric uncertainties, only binaries with mass ratios sufficiently large that they lie more than a few  $\times 0.01$  mag in color from the main sequence peak remain after this subtraction – experiments with synthetic CMDs (see below) suggest a limiting mass ratio of  $q \sim 0.5$ . We measured binary fractions of  $\approx 40\%$  for each of our three clusters, from  $\sim 1500$  stars per histogram. Unresolved binaries can strongly influence a cluster’s MSTO morphology and it is therefore important to assess whether these significant inferred populations can explain the peculiar MSTOs. This is unlikely to be the case, since inspection of Fig. 1 reveals that each peculiar MSTO clearly branches from the *single star* main sequence rather than from the binary sequence. We explore this question in more detail below with the aid of synthetic CMDs.

The most straightforward interpretation of our CMDs is that each cluster possesses at least two stellar populations with very similar  $[\text{Fe}/\text{H}]$  but differing ages. Since the possibility of variations in other chemical abundances is as-yet unconstrained, in what follows we adopt the simplest assumption of complete chemical homogeneity in each system.

To quantify the properties of each cluster’s stellar populations in this scenario, we generated a grid of isochrones in the ACS/WFC (F435W, F814W) plane spanning certain ranges

of age and  $[M/H]$ , and searched this grid to find the isochrone with a shape most closely matching that of the relevant CMD. We adopted recent isochrones from the Padova group (Marigo et al. 2008), using their interactive web form (<http://stev.oapd.inaf.it/cmd>) to generate a fine grid sampling an age range  $1.0 \leq \tau \leq 3.0$  Gyr at intervals of 0.1 Gyr, and a metal abundance range  $0.0025 \leq Z \leq 0.0095$  at intervals of  $\Delta Z = 0.0005$ . These values are appropriate for NGC 1846 and 1783 which have  $\tau \sim 1.5 - 2.0$  Gyr and  $[M/H] \sim -0.4$  (e.g., Mackey & Broby Nielsen 2007; Mucciarelli et al. 2007), as well as for NGC 1806 which is poorly studied but possesses a very similar CMD to that of NGC 1846.

Full details of the isochrone fitting procedure are presented by Mackey & Broby Nielsen (2007). For a given cluster we first matched isochrones to the upper MSTO branch; for NGC 1783 we used the upper envelope of the MSTO with the aim of determining the maximum age spread allowed by the width of this feature. Having calculated the necessary shifts in color and magnitude required to overlay the best-fitting isochrone to the upper MSTO branch, we next applied our technique to the lower MSTO branch (the lower envelope of the MSTO for NGC 1783) with the added constraint that the best-fitting isochrone must have equivalent such shifts. This ensured a consistent solution for each cluster in the absence of any significant line-of-sight depth or differential reddening.

Our results are presented in Fig. 2. In all three cases the highest quality solutions were for  $Z = 0.0075$  isochrones. This corresponds to  $[M/H] \approx -0.40$ , which, as noted above, matches previous spectroscopic and photometric estimates for both NGC 1846 and 1783. In NGC 1846 and 1806, the difference in age between the two MSTO branches is  $\approx 300$  Myr, with the oldest branch representing a population of age  $\sim 1.9$  Gyr and the youngest branch a population of age  $\sim 1.6$  Gyr in both clusters. In NGC 1783, the upper and lower envelopes of the MSTO imply a maximum age spread of  $\approx 400$  Myr, with mean age  $\sim 1.8$  Gyr. Mucciarelli et al. (2007) previously found  $\tau \approx 1.4 \pm 0.2$  Gyr for this cluster using isochrones from the Pisa Evolutionary Library with mild overshooting.

Our best-fitting isochrones match the cluster main-sequences, MSTOs, SGBs, lower RGBs, and red clumps well. The primary discrepancy between the isochrones and CMDs occurs in each case on the upper RGB where the isochrones appear bluer than the observed stars. This may represent some unidentified limitation in either the stellar models or our photometry. Selecting isochrones sufficiently metal-rich to closely trace the upper RGB sequences results in badly degraded fits to the other CMD regions, particularly the main-sequences and MSTO shapes. Our fitting technique allows rough uncertainties to be placed on our best values for age and metal abundance. Moving to isochrones adjacent on the grid to the best models already leads to noticeably poorer fits – hence we conservatively estimate random uncertainties of  $\pm 0.001$  in  $Z$  and  $\pm 0.1$  Gyr in relative age.

We next constructed synthetic CMDs to investigate the role played by unresolved binary stars around the MSTO regions, and in particular investigate whether these objects might reproduce the observed MSTO structures. To do this we generated 5000 stellar detections of which 2000 (40%) were unresolved binaries. These numbers approximately match those for the CMD of NGC 1846. We drew single star and primary masses (and hence luminosities) randomly from a uniform distribution along the  $Z = 0.0075$ ,  $\tau = 1.9$  Gyr isochrone, which best-fit the lower MSTO branch in NGC 1846. In the scenario where the MSTO structure is due to binaries, the lower MSTO branch must represent single stars and the upper branch the binary sequence. To produce the binary sequence we generated a secondary star for each primary by randomly selecting a mass ratio from a uniform distribution in the range  $0.5 - 1.0$ . This synthesis procedure is clearly simplistic – more realistic would be to generate stellar masses along the isochrone by randomly selecting from an appropriate mass function, as well as allowing a non-uniform distribution of mass ratios. We emphasize, however, that our aim here is to observe the area on the CMD occupied by the binary sequence. Varying the generation algorithms presently represents an unnecessary level of complexity.

The upper row in Fig. 3 shows our results. The left panel is the synthetic CMD generated as described above. In the right panel we added random photometric uncertainties to the F435W and F814W magnitudes of each star in this synthetic CMD by measuring the uncertainties determined by DOLPHOT for detected stars in NGC 1846 of equivalent brightness and color, and then generating errors from Gaussian distributions with these widths. These plots clearly demonstrate that unresolved binaries cannot alone reproduce the peculiar MSTO structures. Specifically, the binary sequence does not result in a distinct branch above and to the blue of the lower MSTO branch, as is observed for NGC 1846 (Fig. 1).

We next altered our synthesis procedure to use both best-fitting isochrones for NGC 1846 (Fig. 3, lower panels). This new CMD closely resembles the observed CMD, demonstrating that two stellar populations in NGC 1846 (and by extension NGC 1806) are necessary to explain the observed MSTO structure. At least some of the spread of stars between the two branches in NGC 1846 must be due to unresolved binaries; however, it is intriguing that the two branches each appear to have a larger spread than those in the synthetic CMD, which are quite well defined even with the addition of photometric uncertainties. We do not assert here that this spread is intrinsic, merely that it is worthy of more detailed investigation.

#### 4. Concluding remarks

In this Letter we have demonstrated that three rich intermediate-age LMC star clusters are comprised of multiple stellar populations. Several other LMC objects with similar prop-

erties have previously been tentatively identified. The MSTO in NGC 2173 ( $\tau \sim 1.5$  Gyr) suggests a possible  $\sim 300$  Myr internal age dispersion (Bertelli et al. 2003), while NGC 1868 may exhibit a weak secondary MSTO (Santiago et al. 2002). The young cluster NGC 2011 apparently possesses twin main sequences (Gouliermis et al. 2006).

It is difficult to imagine how our three LMC clusters, each an order of magnitude less massive than the peculiar Galactic globulars, might have retained sufficient gas to undergo multiple widely-separated episodes of star formation. Previous work has shown that the time-dependent potential of a forming star cluster may allow a population of older field stars to be captured (e.g., Pflamm-Altenburg & Kroupa 2007); however, such models cannot convincingly account for the large fraction of captured stars ( $\sim 50\%$ ) required for our clusters, nor the apparent homogeneity in age and metal abundance of the older population within each cluster. A plausible alternative to these suggestions is that each of our three objects is the merger product of two or more clusters formed separately within a single giant molecular cloud (Mackey & Broby Nielsen 2007). The LMC possesses numerous “double” star clusters (e.g., NGC 1850) and its low tidal field could facilitate such mergers. Large-scale realistic  $N$ -body modelling, along with measurements of the structures and internal kinematics of the three present clusters should allow strong constraints to be placed on this possibility.

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*Facilities:* HST (ACS).

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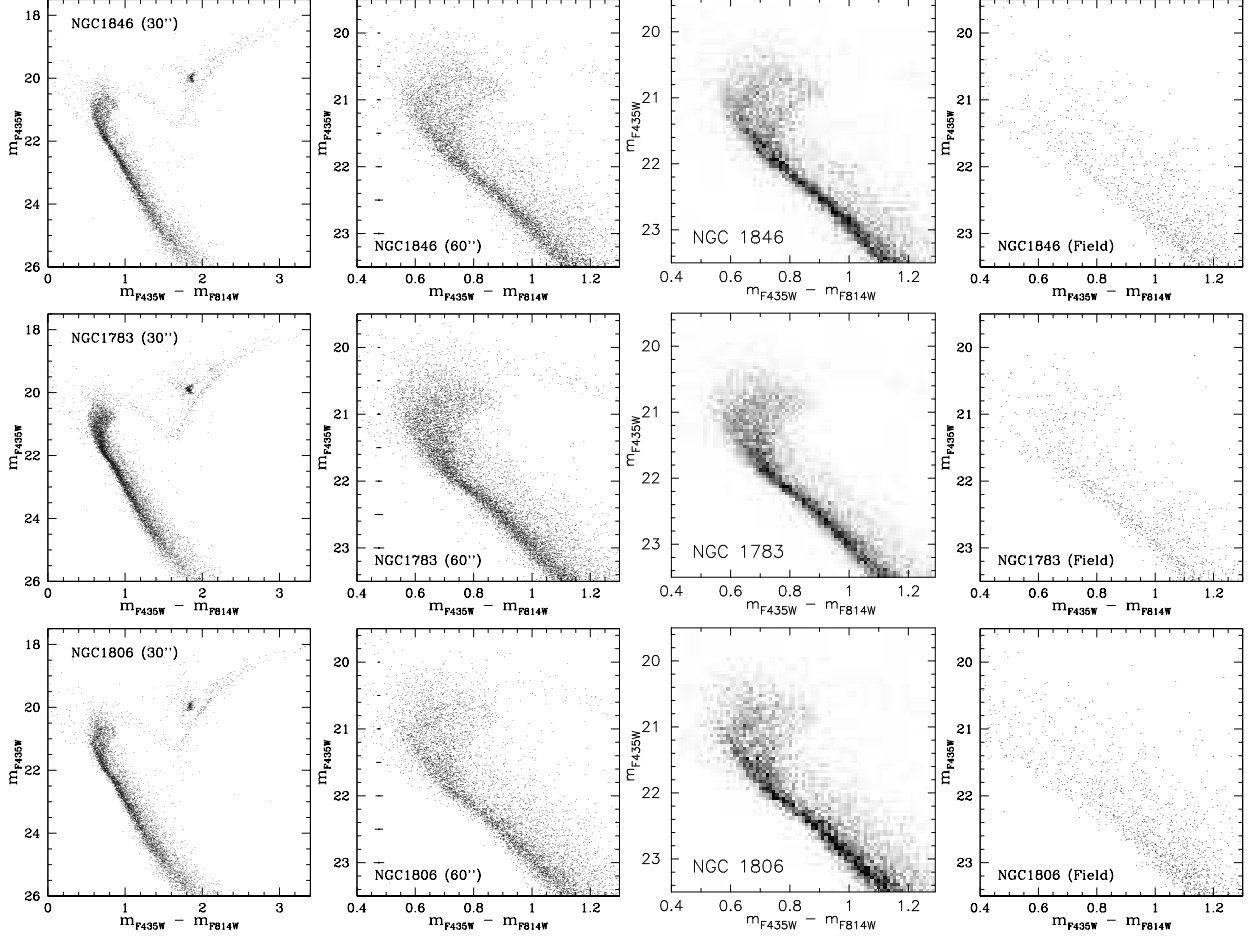


Fig. 1.— ACS/WFC CMDs and Hess diagrams for NGC 1846, 1783, and 1806. Radial cuts of 30'' or 60'' have been imposed as marked. In the second column the sizes of typical photometric uncertainties are indicated. Each Hess diagram has bin sizes of 0.01 mag in color and 0.05 mag in  $m_{F435W}$ . The field CMDs consist of stars taken as far as possible from each cluster center (typically beyond  $\sim 120''$ ) over areas equivalent to those used for the central MSTO extractions.

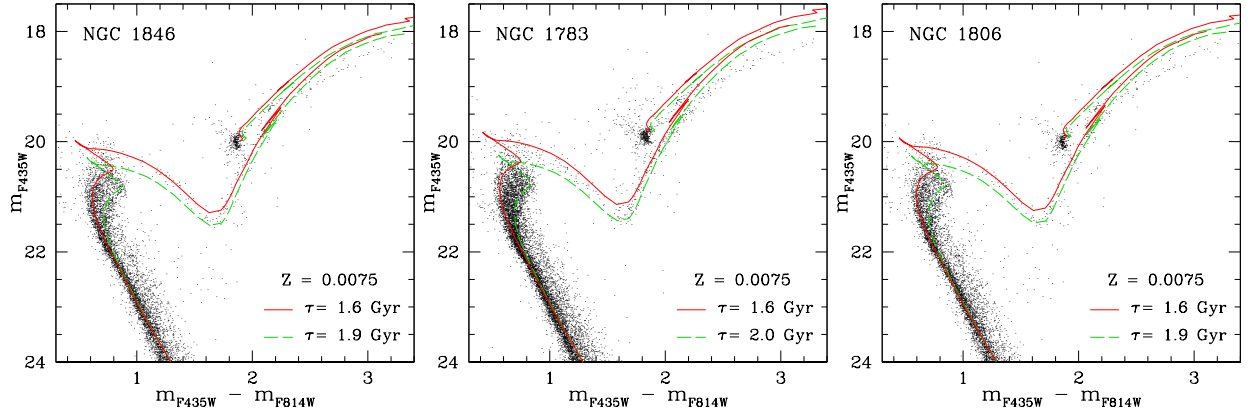


Fig. 2.— Best-fitting isochrones from Marigo et al. (2008) overlaid on the three cluster CMDs.

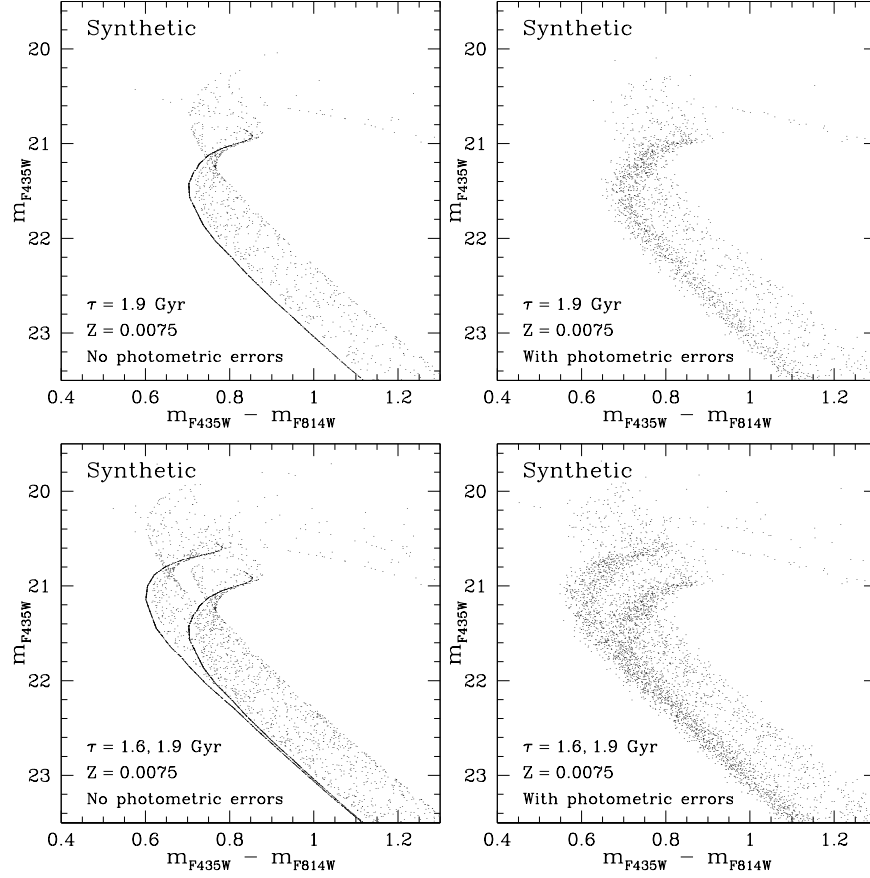


Fig. 3.— Synthetic CMDs calculated as described in the text. A single stellar population cannot reproduce the MSTO structure of, e.g., NGC1846, even with a significant fraction of unresolved binaries; however including two separate populations results in a close match.